# ENVIRONMENTAL ASSESSMENT OF THE INTEGRATION OF ACTIVE SOLAR ENERGY SYSTEMS ON BUILDING ENVELOPES IN SOUTHERN EUROPE

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Abstract

This study aims at making an environmental assessment of the integration of active solar energy systems on building envelopes in southern Europe. More specifically, it focuses on the investigation of shading and insolation of indoor spaces in relation to the energy requirements and the visual comfort of inhabitants. For the needs of the present research, five active solar systems and three representative space typologies were selected for in-depth investigation. Autodesk Ecotect Analysis software v.5.2 and Desktop Radiance v2.0 Beta were used for the simulations. The simulation results are presented and discussed comparatively. The findings indicate that the integration of active solar systems contributes to drastic reductions of the cooling and heating loads. In terms of natural lighting, the integration of active solar systems enables high levels of natural lighting, minimizes glare issues in the majority of systems. The research highlights the role of integrated active solar systems in buildings both in the indoor built environment and in energy performance.

*Keywords*: Environmental Assessment, Active Solar Systems, Architectural Integration, Thermal and Visual Comfort, Southern Europe

## 1 INTRODUCTION

The integration of active solar energy systems on building envelopes contributes effectively to the reduction of heating and cooling loads of the building sector, through the in-situ production of energy [1]. Solar energy systems' key role is increasingly becoming evident wherever high values of annual solar energy are recorded [2].

The research investigates the integration of active solar systems in buildings in terms of energy production, shading and insolation of building facades, as well as in terms of visual comfort of inhabitants.

## 2 LITERATURE REVIEW

Apart from their active use, certain active solar systems integrated in building, i.e. BIPV and BISTS, are also suitable to act as passive design elements. A comparative assessment of BIPV and BISTS performed by Vassiliades et al. (2014, 2015) indicates that a number of active solar systems can be viably integrated into the building envelope [3, 4]. The architectural integration of active solar systems is thoroughly analysed in the relevant literature. Bougiatioti and Michael have investigated the architectural integration of active solar systems in building facades and roofs in the Eastern Mediterranean region [5]. An energy performance assessment of photovoltaic panels integrated into shading devices was performed by Mandalaki et al. (2012) [6]. Further research investigates the geometrical optimization of a shading device with integrated PVs in terms of energy production and energy savings resulting from the minimization of direct solar gains and visual comfort conditions [2]. However, related literature on both the active and passive role of solar energy systems remains rather limited. This research aims at making a comprehensive investigation of BIPV and BISTS and at establishing a multi-criteria evaluation methodology of the building integrated active solar energy systems.

## 3 METHODOLOGY

The current study focuses on two main pillars, i.e., the investigation of shading and insolation of glazed surfaces in relation to energy consumption and the investigation of the visual comfort of inhabitants in terms of lighting levels and glare issues.

### 3.1 Building Typologies

Three representative building typologies were selected for in-depth investigation, as shown in Figure 1. Specifically, typology A has plan dimensions of 5m width and 3 m depth, namely, shallow plan; typology B has plan dimensions of 5m width and 5m depth, namely, medium plan; and typology C has plan dimensions of 5m width and 7m depth, namely, deep plan. The height of the space in all three cases is the same, i.e., 3m.

The three spaces have a fully glazed elevation towards the south, while the other three sides were solid walls. The thermal properties of the building envelope elements were selected based on the energy performance of buildings directive 2002/91/EC.

The glazed surface of the building unit was south facing due to the high levels of solar exploitation, as well as to the need for sun protection during the hot summer period in the southern orientation. Increased glare issues in south facing spaces during the entire year render the reduction of unwanted levels of glare and the improvement of visual comfort.

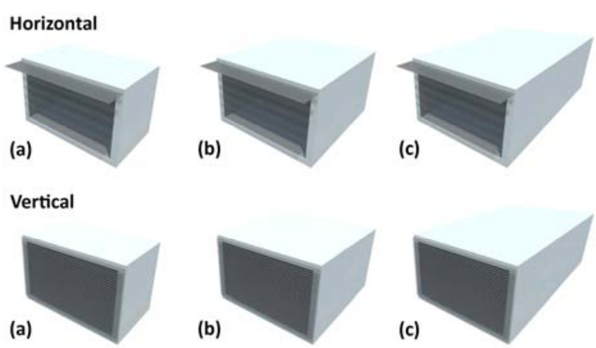


Figure 1. Building integrated active solar systems at horizontal and vertical configuration in the three different building typologies under study, (a) shallow, (b) medium and (c) deep typology.

Two configurations, namely the horizontal and vertical integration, are examined in the investigation of active solar systems (Figure 1). The horizontal configuration refers to the placement of the active solar systems under study in the form of a 1,5 m long horizontal canopy[7]. The vertical layout refers to the placement of active solar systems in front of the glazed surface, or in the glazed surface in the case of specific photovoltaic technologies. The selected configurations ensure 7.5 $m^2$ and 15 $m^2$ of effective surface of active solar systems for horizontal and vertical configurations, respectively.

### 3.2 Technologies

A number of active solar systems that could operate as passive shading devices were selected for simulation purposes. Analysis from previous research work [3], [4], indicates that appropriate BIPV systems include the aSi thin film with 10% of transparency, the monocrystalline with 0.02 m space between the cells and the polycrystalline with 0.05 m space between the cells, while appropriate BIST systems include vacuum tubes and unglazed cylindrical solar collectors.

### 3.3 Simulations

The environmental assessment of active solar systems was carried out through simulations.

*Shading and Insolation*

The shading and insolation strategies were evaluated using shading masks for all active solar systems integrated in the building façade. The shading masks were prepared for high overshadowing accuracy using the stereographic diagram tool of Autodesk Ecotect Analysis software v.5.2. The investigation was performed at 36$^o$ south latitude for representative periods of the year, i.e., solstices and equinoxes at 09:00, 12:00 and 15:00 h.

The active solar systems integrated in the building façades were also examined in terms of energy consumption. Without the integration of any active solar system, the energy consumption was taken as reference value. Heating and cooling loads were calculated using a mixed mode air-condition system with a 95% efficiency rate. The temperature limits were set from 21 to 25 $^o$C according to ASHRAE 55 (2013) standard for 80% occupant thermal acceptability. The annual energy consumption, i.e., heating and cooling loads, is presented in kWh per square meter of the plan area (kWh/$m^2$), allowing the comparative evaluation of the systems.

### *Energy Consumption*

Autodesk Ecotect Analysis software v5.2 [8], was used for the simulation of the passive behaviour of active solar systems. Desktop Radiance v2.0 Beta [9] was used for natural lighting analysis, while Ecotect software v5.2 was employed as a modelling and visualization tool.

### *Visual Comfort*

The evaluation of visual comfort was performed for representative periods of the year, i.e., solstices and equinoxes at solar noon. The sky model was set as cloudy for winter, intermediate for spring and sunny for the summer period, thus providing results for the climatic extremes during the entire year; the reference standard year of Nicosia was used. The typical reflectance values for representative interior materials were used based on literature references, using material files for Desktop Radiance software. Calculations were made using three indirect reflections, employing an analysis grid at 0.75 m height from floor level.

Efficient lighting levels are taken to be 75% of the area of the plan exceeding 500 Lux and minimum possible percentage of the area exceeding 3000 Lux since over-illumination leads to potential glare issues [10].

Moreover, the preferred conditions for the most efficient function of the space are indicated by daylighting performance indicators, i.e., the daylight factor (DF) and the uniformity daylight factor (UDF). The daylight factor, DF, expresses the ratio of interior illuminance on a horizontal surface, to the exterior illuminance on a horizontal surface under an overcast CIE sky. An average DF of 2% for 75% of the space is deemed as acceptable, according to CIBSE [11]. Uniformity Daylight Factor, UDF, indicates the homogeneity level of lighting distribution, expressed by the singular minimum Lux value divided by the average value of the entire plan, i.e., UDF = DFmin / DFmean. According to BREEAM 2.08, the required UDF for an efficient work space should be at least 0,4 [12].

## 4 RESULTS

### 4.1 Shading and Insolation

The simulation results of the shading and insolation of indoor spaces, as well as of the visual comfort of occupants, are presented in Table 1 and discussed comparatively below.

Table 1. Shading percentages for horizontal and vertical configuration of the active solar systems under study.

| Period | Time | Active Solar System | | | | |
|---|---|---|---|---|---|---|
| | | PV | | | STS | |
| | | aSi Thin Film | Monocrystalline | Polycrystalline | Unglazed | Vacuum Tube |
| **Horizontal Configuration** | | | | | | |
| Winter Solstice | 09:00 | 29% | 29% | 29% | 29% | 29% |
| | 12:00 | 30% | 32% | 24% | 32% | 28% |
| | 15:00 | 39% | 34% | 37% | 39% | 37% |
| Autumn Spring Equinox | 09:00 | 58% | 58% | 58% | 58% | 58% |
| | 12:00 | 69% | 70% | 62% | 57% | 53% |
| | 15:00 | 76% | 75% | 69% | 70% | 68% |
| Summer Solstice | 09:00 | 96% | 96% | 96% | 96% | 96% |
| | 12:00 | 95% | 94% | 85% | 88% | 86% |
| | 15:00 | 99% | 99% | 99% | 99% | 99% |
| **Vertical Configuration** | | | | | | |
| Winter Solstice | 09:00 | 29% | 29% | 29% | 67% | 29% |
| | 12:00 | 15% | 15% | 15% | 60% | 52% |
| | 15:00 | 30% | 30% | 30% | 72% | 55% |
| Autumn Spring Equinox | 09:00 | 58% | 100% | 64% | 97% | 58% |
| | 12:00 | 41% | 100% | 69% | 96% | 61% |
| | 15:00 | 59% | 100% | 72% | 95% | 73% |
| Summer Solstice | 09:00 | 96% | 96% | 96% | 96% | 96% |
| | 12:00 | 86% | 96% | 88% | 100% | 94% |
| | 15:00 | 98% | 99% | 98% | 99% | 99% |

Shading through the application of shading masks indicates that the horizontal integration of active solar systems during the winter solstice provides limited shading of approximately 28%, i.e., from 24% to 39%, which allows adequate insolation. During the autumn and spring equinoxes, the active systems provide shading of approximately 64%, i.e., from 53% to 76%, while during the summer solstice, the integration of active systems provides shading of approximately 95%, i.e., from 85% to 99%. The shading results do not significantly differ between the active solar systems under study or between different times of the day. During the winter solstice, photovoltaic systems in the vertical layout provide limited shading of approximately 25%, i.e., from 15% to 30%, which allow adequate insolation. Solar thermal systems provide high percentages of shading, i.e., approximately 45% for vacuum tubes and 66% for unglazed cylindrical solar collectors. The systems in question are unsuitable for use during the winter. In the autumn and spring equinoxes, specific active solar systems, i.e., aSi thin film, polycrystalline and vacuum tubes, provide a shading of approximately 62% i.e., from 41% to 72%. By contrast, monocrystalline and unglazed cylindrical solar collectors provide high levels of shading, i.e., 100% and 96% respectively. During the summer solstice, the integration of all active solar systems provides shading of 96%, i.e., from 86% to 100%, and ensures adequate protection from solar gains.

## 4.2 Energy Consumption

The investigation of energy consumption aims to define the positive contribution of each system as a passive shading device. More specifically, it is expected that the cooling loads required during the warm period will be reduced due to the sun protection offered by the systems. The heating loads required during the cold period will increase due to the reduction of direct solar gains. The results are presented in Figure 2.

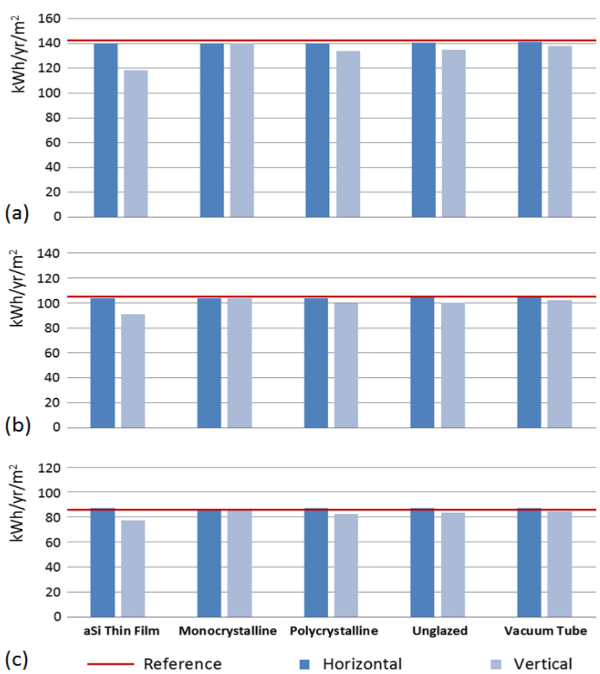


Figure 2. Energy consumption of the building typologies under study,(a) shallow, (b) medium and (c) deep plan, for horizontal and vertical configuration of active solar systems.

The annual energy consumptions of the three building typologies in horizontal configuration, show that the systems' total annual contribution is negligible, fluctuating at ±2% of the consumption before the integration of the system.

By contrast, the vertical integration indicates a positive contribution in the annual energy consumption. Specifically, the positive contribution of the vertical integration of the systems ranges from 1.5-23.2 kWh per square meter of the plan area in the shallow plan to 0.2-13.1 kWh/m$^2$ in the medium plan and to 0.1-8.7 kWh/m$^2$ in the deep plan. It is also noted that the positive contribution of the vertically integrated aSi thin film is comparatively higher than that of the other systems.

## 4.3 Visual Comfort

### *Lighting Levels*

The integration of the active solar systems in both horizontal and vertical configuration, manages to keep the high levels of natural lighting in the indoor space. In all cases, the daylight levels exceed 500 lux for more than 75% of the plan area, satisfying international lighting standards. The integration of active solar systems eliminates high daylight levels (> 3000 lux) and minimizes glare issues and improves visual comfort.

### *Daylight Performance Indicators*

The daylight factor (DF) and uniformity daylight factor (UDF) were calculated under overcast conditions for all three typologies without any shading device (reference scenarios) and with the integration of active solar systems in both horizontal and vertical configuration. Table 2 shows the comparative evaluation.

Table 2. Daylight performance indicators of the building typologies under study for horizontal and vertical configuration of active solar systems.

| **Building Typology** | **Reference Scenario** Without any Shading Device | **Active Solar System** | | | | |
|---|---|---|---|---|---|---|
| | | **PV** | | | **STS** | |
| | | aSi Thin Film | Monocrystalline | Polycrystalline | Unglazed | Vacuum Tube |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Horizontal Configuration** | | | | | | |
| | Percentage of space area with DF > 2% | | | | | |
| Shallow | 100% | 100% | 100% | 100% | 100% | 100% |
| Medium | 100% | 100% | 100% | 100% | 100% | 100% |
| Deep | 95% | 81% | 93% | 94% | 82% | 88% |
| | Uniformity Daylight Factor (UDF) | | | | | |
| Shallow | 0.42 | 0.47 | 0.49 | 0.45 | 0.45 | 0.46 |
| Medium | 0.31 | 0.35 | 0.37 | 0.32 | 0.34 | 0.34 |
| Deep | 0.21 | 0.27 | 0.26 | 0.24 | 0.24 | 0.25 |
| **Vertical Configuration** | | | | | | |
| | Percentage of area with DF > 2% | | | | | |
| Shallow | 100% | 0% | 74% | 100% | 100% | 100% |
| Medium | 100% | 0% | 41% | 94% | 78% | 100% |
| Deep | 95% | 0% | 32% | 57% | 65% | 77% |
| | Uniformity Daylight Factor (UDF) | | | | | |
| Shallow | 0.42 | 0.57 | 0.31 | 0.38 | 0.72 | 0.51 |
| Medium | 0.31 | 0.40 | 0.24 | 0.24 | 0.43 | 0.39 |
| Deep | 0.21 | 0.25 | 0.16 | 0.17 | 0.28 | 0.24 |

The DF indicator of the spaces without the integration of any shading device is observed to exceed 2% DF is 100% in the shallow plan, 100% in the medium plan and 95% in the deep plan. In the case of the shallow plan the UDF value exceeds the threshold of 0.40, i.e., 0.42 UDF, indicating satisfactory uniformity of daylight. In the case of medium and deep plan the UDF is 0.31 and 0.21 respectively, failing to reach the threshold of 0.40 UDF.

In the horizontal configuration, the lighting level analysis shows that the percentage of the plan area exceeding 2% DF remains at 100% in the case of the shallow and medium plan, while, in the case of the deep plan it remains at high levels, i.e., 81% to 94%. Moreover, the uniformity daylight factor increases after the integration of active solar systems in horizontal configuration from 0.42 UDF in the reference case to 0.45 - 0.49 UDF in the case of the shallow plan, from 0.31 UDF to 0.32 - 0.37 UDF in the case of the medium plan and from 0.21 UDF to 0.24 - 0.27 UDF in the case of the deep plan. In the case of the shallow plan, satisfactory UDF values exceeding the threshold of 0.40 are recorded after the integration of active solar systems in horizontal configuration. Despite the increase of the UDF values in the cases of the medium and deep plan, the UDF values remain below the threshold of 0.40 UDF and thus fail to satisfy the lighting standards.

In the vertical configuration, photovoltaics and solar thermal systems demonstrate different performance in terms of lighting levels regulation. The lighting level analysis shows that the photovoltaics systems are not effective solutions for lighting regulation, since the percentage of the plan area exceeding 2% DF is significantly reduced. In the majority of cases, the UDF values decreased after the integration of the photovoltaics systems in vertical configuration.

The lighting level analysis shows that the integration of solar thermal systems is effective for lighting levels regulation since the percentages of the plan area exceeding 2% DF remain at high levels. The percentage of the plan area exceeding 2% DF remains at 100% in the case of the shallow plan, at 78% to 100% in the case of the medium plan and at 65% to 77% in the case of the deep plan. Moreover, the uniformity daylight factor increases significantly after the integration of solar thermal systems in vertical configuration from 0.42 UDF in the reference case to 0.51 - 0.72 UDF in the case of the shallow plan, from 0.31 UDF to 0.37 - 0.43 UDF in the case of the medium plan and from 0.21 UDF to 0.24 - 0.28 UDF in the case of the deep plan.

In the case of the shallow and medium plan, high UDF values, approaching or exceeding the threshold of 0.40, are recorded after the integration of solar thermal systems in vertical configuration. Despite the increase of the UDF values in the case of deep plans, the UDF values remain below the threshold of 0.40 UDF and fail to satisfy the lighting standards.

## 5 SYNOPSIS AND CONCLUSIONS

The research presented investigates the building integration of active solar systems in terms of shading and insolation of building facades and in terms of visual comfort of inhabitants, ensuring thus a comprehensive environmental approach to integrated active solar energy systems.

The investigation of shading and insolation presented indicates that all active solar systems integrated horizontally into the building envelope offer suitable shading and insolation during the cooling and heating period. In the case of vertical integration, better shading and insolation conditions are exhibited throughout the entire year.

The investigation of energy consumption of the building typologies in question shows that the horizontal integration of active solar systems has minimal impact on the annual energy consumption of the three building typologies. In the case of vertical integration of active solar systems, a positive contribution in the reduction of the annual energy consumption is recorded.
The simulation results and the analysis of lighting levels, indicate that the integration of active solar systems in both horizontal and vertical configuration, maintains high levels of natural lighting, i.e., 500 lux for more than 75% of the plan area, while it eliminates extremely high daylight levels, that is > 3000 lux. Moreover, all the active solar systems under study integrated horizontally into the building envelope offer high levels of lighting performance. In the case of vertical integration, better lighting performance is exhibited by solar thermal systems. The integration of both photovoltaic and solar thermal systems in horizontal configuration and the integration of solar thermal systems in vertical configurations, offer higher uniformity daylight factor values, and thus minimize the possibility of glare issues.
In conclusion, the research introduces a comprehensive investigation of BIPV and BISTS and establishes a multi-criteria evaluation methodology for building integrated active solar energy systems. The study presents in a quantitative manner the active and passive role of integrated active solar energy systems and validates the importance of their building integration in buildings of southern Europe.

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